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ZEROPOWER Benchmarking tools

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Short description

This report presents a general benchmarking system to be used to compare the efficiencies of different vibration energy harvester systems.

ZEROPOWER Benchmarking tools

Table of Content

Description of the deliverable

This report presents a general benchmarking system, i.e. a set of tools and prescriptions that can be used to compare the efficiencies of different energy harvesting systems. This problem is particularly apparent when dealing with vibration energy harvesting. For this reason we concentrate on this technology. In the present literature the performances of vibration harvesters are presented with a number of different figures (power per cubic centimetre, voltage generated, energy density per unitary acceleration, to mention a few). See references for a list of different approaches to the performance assessment problem. Moreover very seldom little or no information is provided on the features of the energy source (spectral density, statistical distribution, …). In this report we start with a brief review of the state-of-the-art for the efforts to introduce standards in the field of energy harvesting. Following we present a schematic representation of the vibration energy harvesting task and introduce the relevant quantities to be used for defining a benchmarking system. Finally we propose a viable benchmarking system with some examples.

Progress towards objective

1 Ongoing effort for standardizing the field of energy harvesting

Although our interest is limited to defining a benchmarking system and thus much more limited that the introduction of a standardization in the field of energy harvesting we believe it is useful to start this report with a brief survey of current effort for introducing an international standard.

In 2008-2009 a group of companies, mainly in UK took the initiative for the definition of a new set of standards in the field of energy harvesting for powering mobile devices. The Working Group mission is to develop standards to enable users and suppliers to compare, specify and interface power/energy sources for “non line powered, low power, wireless sensor nodes (WSN)” (see Freeland, 2010).

On 4 Nov 2009 this group (Power Sources Working group) met the ISA100 Main Committee in Denver and on Tue 8th Feb 2010 they met again in Orlando (FL).

The objectives of the activity of the working group are:

–Develop and Publish standards that permit interchangeability of Power Modules for WSN’s.

–Develop and publish standards for specifying performance of power/energy sources

After the meeting with the ISA100 Main Committee the working group has become a subgroup of a more general effort of ISA100 and specifically the WG 18 (ISA 100.18):

- WG 18 - Power Sources (ISA100.18)

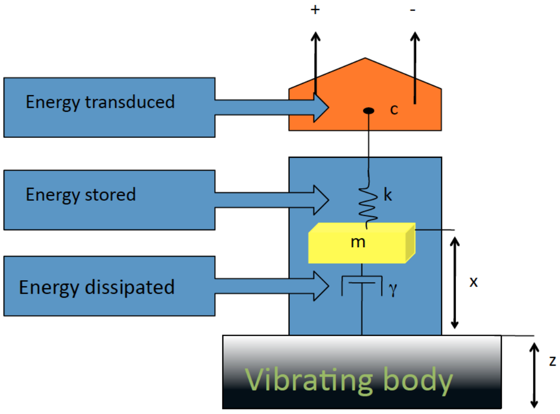
The WG 18 is coordinated by: Roy Freeland (with Perpetuum) and Sicco Dwars (with Shell).

Roy Freeland is a member of the ZEROPOWER SAC. He has recently declared: “*The ISA100.18 Working Group is preparing standards and information documents on power sources for WSNs. Key objectives are to define specifications for the interchangeability of various power sources, including batteries, energy harvesters, and other possible types, such as 4-20mA loops, and to define performance specifications so users can compare different harvesters and choose the optimum power source for each application. The working group is cooperating with a range of organizations, including VDI and NAMUR on battery standards for WSNs and other organizations using 802.15.4, such as WirelessHART and Zigbee as well as other low power wireless protocols.”*

2 Schematic representation of vibration energy harvesting task

in the following we present a schematic representation of the vibration energy harvesting task. In order to reach such an understanding we start analyzing what are the main features of the vibration energy available for harvesting activities. It is well known that among the renewable energy sources, kinetic energy is undoubtedly the most widely studied for applications to the micro-energy generation.

Kinetic energy harvesting requires a transduction mechanism to generate electrical energy from motion and the generator requires a mechanical system that couples environmental displacements to the transduction mechanism.



Specifically, the design of the mechanical system is realised with the aim of maximising the coupling between the kinetic energy source and the transduction mechanism and depends entirely upon the characteristics of the kinetic energy source under consideration. At micro and nanoscale kinetic energy is usually available as random vibrations or displacement noise. In order to explore the wide panorama of available vibrations, our laboratory has started the construction of a general database of ambient vibrations. It is well known that vibrations potentially suitable for energy harvesting can be found in numerous aspects of human experience, including natural events (seismic motion, wind, water tides), common household goods (fridges, fans, washing machines, microwave ovens etc), industrial plant equipment, moving structures such as automobiles and aeroplanes and structures such as buildings and bridges. Also human and animal bodies are considered interesting sites for vibration harvesting. As an example in figure 2 we present three different spectra computed from vibrations taken from a car hood in motion, an operating microwave owen and a running train floor. All these different sources produce vibrations that vary large in amplitude and spectral characteristics. In the example, the car hood present a distinct spectral peak structure (at approximately 30 Hz, 50 Hz and 80 Hz) above a slowly varying background. On the other hand the spectral distribution of the vibration energy of the train floor shows a large bump between 1 Hz and 2 Hz and, afterwards stays pretty high and flat up to approximately 1 kHz. These two very distinct behaviours reflect in the capability of providing a viable source for energy harvesting. Generally speaking the human motion is classified among the high-amplitude/low-frequency sources.

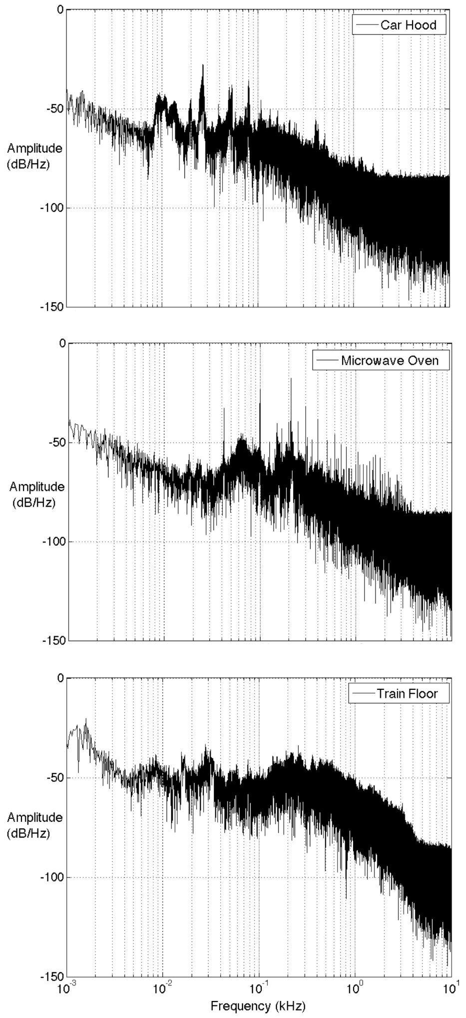


Figure 1. Vibration power spectra. Figure shows acceleration magnitudes (in db/Hz) vs. frequency for three different ambient vibrations: car hood in motion, operating microwave oven, train flor during motion.

An interesting limiting case of kinetic energy present in the form of random vibration is represented by the thermal fluctuations at the nanoscale. This very special environment represents also an important link between the two most promising sources of energy at the nanoscale: thermal gradients and thermal non-equilibrium fluctuations (Casati et al, 2008).

Energy management issues at nano scales require a careful approach. At the nano scale, in fact, thermal fluctuations dominates the dynamics and concepts like “energy efficiency” and work-heat relations imply new assumptions and new interpretations. In recent years, assisted by new research tools, scientists have begun to study nanoscale interactions in detail. Non-equilibrium work relations, mainly in the form of “fluctuation theorems”, have shown to provide valuable information on the role of non-equilibrium fluctuations.

In order to explore viable solutions to the harvesting of energies down to the nano scales a number of different routes are currently explored by researchers world wide. In this report we focus on **nano-mechanical nonlinear vibration oscillators**. Nano scale oscillators have been considered a promising solution for the harvesting of small random vibrations of the kind described above since few years. A significant contribution to this area has been given by Zhong Lin Wang and colleagues at the Georgia Institute of Technology[25]. In a recent work[26] they grew vertical lead zirconate titanate (PZT) nanowires and, exploiting piezoelectric properties of layered arrays of these structure, showed that can convert mechanical strain into electrical energy capable of powering a commercial diode intermittently with operation power up to 6 mW. The typical diameter of the nanowires is 30 to 100 nm, and they measure 1 to 3 μm in length. A different nano-mechanical generator has been realized by Xi Chen and coworkers[27], based on PZT nanofibers, with a diameter and length of approximately 60 nm and >500 μm, aligned on Platinum interdigitated electrodes and packaged in a soft polymer on a silicon substrate. The PZT nanofibers employed in this generator have been prepared by electrospinning process and exhibit an extremely high piezoelectric voltage constant (g33: 0.079 Vm/N) with high bending flexibility and high mechanical strength (unlike bulk, thin films or microfibers). Also Zinc-Oxide (ZnO) material received significant attention in the attempt to realize reliable nano-generators. Min-Yeol Choi and coworkers[28] have recently proposed a transparent and flexible piezoelectric generator based on ZnO nanorods. The nanorods are vertically sandwiched between two flat surfaces producing a thin mattress-like structure. When the structure is bended the nanorods get compressed and a voltage appear at their ends.

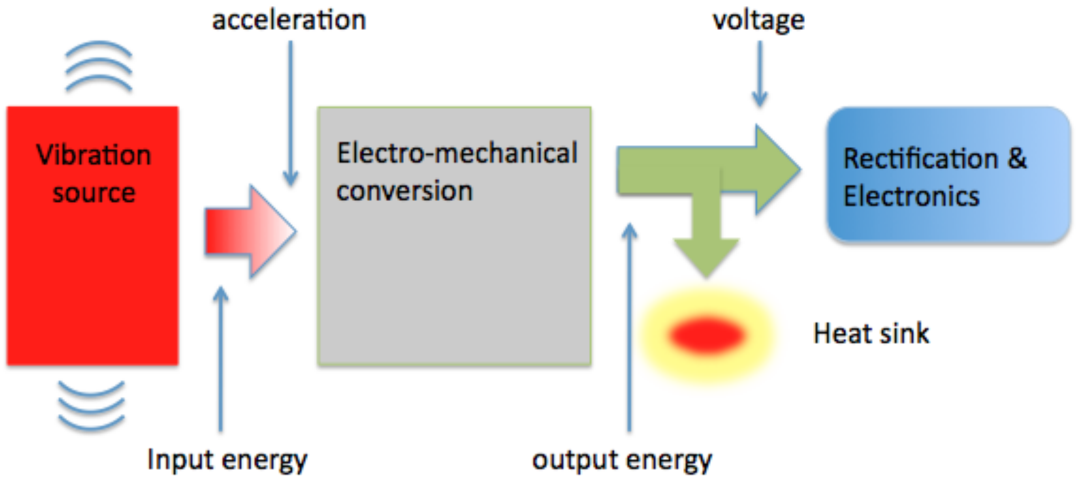


Figure 2. Schematics of the energy flux through a vibration energy harvester.

At difference with these existing approaches, in the NANOPOWER project attention is focussed mainly on the dynamics of nano scale structures and it concentrates in geometries that allowed a clear nonlinear dynamical behaviour, like bistable membranes. In fact[29,30] a general class of bistable/multistable nonlinear oscillators have been demonstrated to have noise-activated switching with an increased energy conversion efficiency. In order to reach multi-stable operation condition, in NANOPOWER a clamped membrane is realised under a small compressive strain, forcing it to either of the two positions. The membrane vibrates between the two potential minima and has also intra-minima modes. The kinetic energy of the nonlinear vibration is converted into electric energy by piezo membrane sandwiched between the electrodes.

On a more general base, regardless of the specific geometry that realizes the micro/nano mechanical oscillator the vibration energy harvesting task is achieved by means of inertial generators with the mechanical component attached to an inertial frame that acts as the fixed reference. The inertial frame transmits the vibrations to a suspended inertial mass, producing a relative displacement between them.

Based on this general understanding we can schematize the vibration energy harvesting task as represented in Figure 2 where the piezoelectric energy producing process is specifically considered: a certain amount of energy is available under the form of vibration. The input energy is processed by the electro-mechanical conversion process and at the output we found part of the energy that is transformed into electric energy and part that is output in the form of heat (dissipated energy).

In order to quantify the performances of a vibration energy harvester we need to identity what are the relevant quantities that can be measured.

Two main assumptions are important in order to generalize our approach:

1) The vibration energy harvester is coupled to the input energy source in such a way that the vibration source is unaffected by the coupling. As a consequence we can treat the vibration source as a pure acceleration source. This can be realized if the inertial mass of the vibration harvester is much smaller than the inertia of the vibration source.
2) The "Rectification & electronics" box is treated as a purely resistive load with resistance R. This approximation is useful to decouple the rectification problem from the voltage generation.

The "Rectification & electronics" box in Figure 2 realizes the very important task of adjusting the output voltage to the needs of device that has to be powered with the harvesting activity. Although this is an important and useful task, its treatment is beyond the scope of this report and will not be treated here.

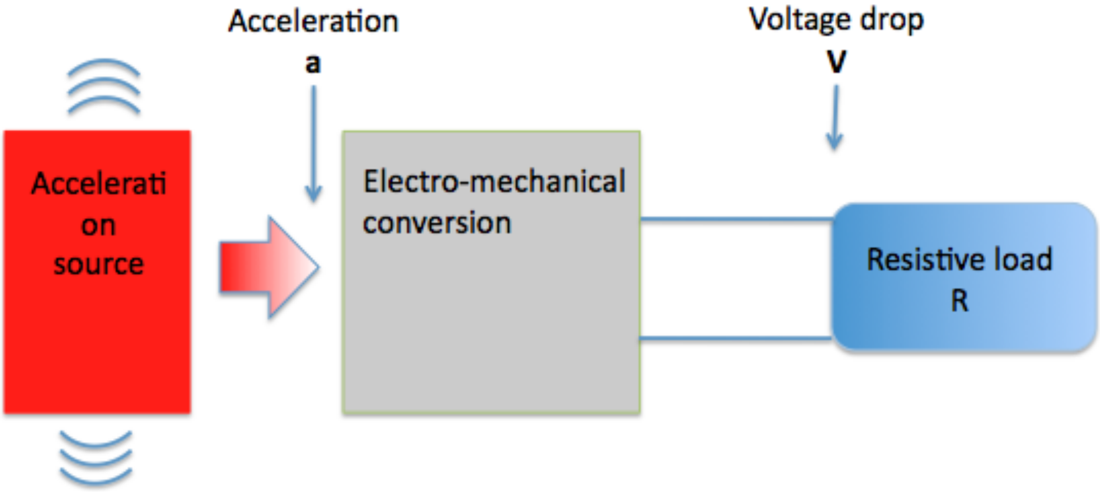


Figure 3. Reduced scheme of the vibration energy harvester.

3 Benchmarking system

Based on these two previous assumptions we are now in position to identify the relevant quantities for designing a proper benchmarking system for assessing performances of vibration harvesting prototypes. This process is now illustrated in Figure 3. The vibration energy harvesting task is thus reduced to the measurement of one relevant quantity, V(t) and by controlling two quantities a(t) and R.

Specifically the performances of an energy harvester can be quantified by monitoring the output voltage V(t) once is known the input acceleration a(t) and the resistive load R.

For what concerns the resistive load R, there are two different cases that are particularly relevant for benchmarking purposes. The first case is the infinite load $R = \infty$ condition. In this case the power transferred to the load, being expressed by $W = V^2/R$ is zero. This condition can be realized in the open circuit state o, practically, by closing the piezoelectric component on a large (100 MΩ) resistive load. Another interesting condition for the choice of the resistive load is the selection of an optimized value of the resistive load with respect to the power transferred to the load itself. This is known as matched impedance condition $R = R_M$

For what concerns the choice of the acceleration a(t), instead of using an harmonic signal A sin(ωt) that, as we have seen, is far from the most common wide band vibration signal, we propose to use a random signal ξ(t) characterized by the following conditions (Cottone et al, 2009):

Mean value $<\xi> = 0$

Variance $<\xi^2> = \sigma^2$

Autocorrelation function $<\xi(t)\xi(t+\tau)> = \sigma^2 e^{-\frac{t}{\tau}}$

Gaussian probability density function $P(\xi) = \frac{1}{\sqrt{2\pi\sigma^2}} e^{-\frac{\xi^2}{2\sigma^2}}$

This is usually known as exponentially correlated noise (Fox et al, 1988) and is a good approximation to a number of real vibration signals.

Conclusion

In this report we introduced the basic elements for a general benchmarking system to be used to compare the efficiencies of different vibration energy harvester systems. This benchmarking system has been designed having in mind specifically the piezoelectric vibration harvesting technology but its validity is more general and is applicable to other physical principles as well.
The benchmarking procedure is here briefly summarized as follows:

1) The vibration harvesting device is contacted with a rigid surface that vibrates according to an acceleration a(t).
2) The voltage signal at the output of the vibration harvesting device is measured across a load resistance R.
3) The performances of vibration harvesting devices are ranked according to the value of V_{rms}, for the same a(t) and R.
4) The choice of a(t) is recommended to be an exponentially correlated, Gaussian distributed noise characterized by three parameters: zero mean, variance σ^2 and correlation time τ.

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